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DEVELOPMENT OF AN INFLATABLE HEAD/NECK RESTRAINT SYSTEM FOR EJECTION SEATS

(UPDATE)

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A ring-shaped inflatable head/neck restraint system for ejection seats is being developed at the Aircraft & Crew Systems Technology Directorate, NADC. The purpose of this system is to reduce neck injuries due to violent forward head rotation at the time of ejection thrust and parachute opening shock. Inflation of the neck ring will be conducted by a solid propellant gas generator. Design considerations include form-and-fit, cost effectiveness, packaging and integration into life support equipment.

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INTRODUCTION

The objective of an operational head restraint is to limit forward head-and-neck rotation on the crew member during ejection and at the time of parachute opening shock, thereby reducing the probability of injury to the neck muscles and cervical portion of the spine.

When the center of gravity (CG) of the helmet/head mass is forward of the ejection thrust vector or forward of the parachute opening force vector, the head is apt to rotate violently forward. Occurrence of violent head rotation during ejection is encouraged by actuation of the lower ejection handle, the headrest design and movement of the crewman's helmet. Head rotation is most susceptible during lower ejection handle actuation because of the tendency to hunch forward while pulling on the handle; as a result, the CG of the head may move forward of the ejection thrust line. Additionally, the headrests on current ejection seats are designed to allow the crew member to maintain visual contact with the instrument panel displays during catapault launches and carrier landings. In fulfilling this requirement, the headrest is designed to restrain the crewman's head forward of a normal seating position; such a position makes the head susceptible to rotation. Whenever the helmet shifts forward on the head under the influence of outside forces, the CG of the head/helmet mass may move forward of the ejection thrust vector, resulting in head rotation. For ejections and parachute openings, head rotation may be violent enough to cause the crewman's chin to impact his sternum.

Based on data from the Naval Safety Center, Norfolk, Virginia, there were over 1300 Navy aircraft ejections during the calendar years 1967-1974. Of these ejections, approximately 8 percent resulted in some type of neck injury attributed to ejection or parachute opening forces. The severity of the injuries ranged from neck muscle strains to fractures of cervical vertebrae. It can only be speculated that some downed airmen may have been lost at sea because they could not deploy life support equipment due to incapacitation from head rotation injuries. Along with injury to the neck and spine, violent head rotation can impart shear strains on the brain[1,2] and produce unconsciousness[2].

The reported incidence of such injuries indicates a need for an effective head restraint system. As a consequence, the Aircraft and Crew Systems Technology Directorate (ACSTD) of the Naval Air Development Center (NAVAIRDEVCEN) has been involved in the development of a protective system to eliminate or reduce head rotation injury. The present hardware under development by this activity uses the concept of an inflatable neck collar (or neck bladder). This design is an offshoot of an earlier inflatable chin bag which was originally developed at ACSTD[3]. The chin bag, shown in figure 1, was fastened to the helmet chin strap. Although the depicted configuration was not an optimized

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1. *Holbourne, A. H. S.; Mechanics of Head Injuries, Lancet 245:438-441, 1943.*
2. *Ommaya, A. K. and Hirsch, A. E.; Tolerances for Cerebral Concussion From Head Impact and Whiplash in Primates, J. Biomechanics 4:13-21, 1971.*
3. *Schulman, M. and Hendler E.; Restraint of the Head During Acceleration, paper presented in the Tenth Annual SAFE Symposium Proceedings, Oct 1972.*

FIGURE 1 - Inflatable Chin Bag

design with regard to shape and positioning, it was tested using live subjects on the ACSTD ejection tower facility[3] to demonstrate its improved head restraint characteristics. Because of the experimental nature of these tests, peak ejection force was held to about 6 G's (compared to an actual ejection generating a force of approximately 11 to 14 G's) and the bag was preinflated and positioned before the ejection thrust. Comparison of live subject ejections with and without the bag are shown in figure 2. The most important aspect of the experiment was to show that the chin bag reduced head rotation by 20 deg, demonstrating the feasibility of using an inflatable head restraint. Of interest in figure 2 is the curve of the no helmet subject. Head rotation for this condition was the most limited and supports the argument for a light helmet.

In July and August of 1972, ACSTD conducted numerous ejection tower tests (with ejection forces in the 10 to 12 G range) using a modified inflatable neck collar to protect the human subjects from neck injuries. Although the tests were conducted to acquire data not affiliated with development of the neck collar, analysis of the test films showed that it helped to limit head rotation during ejection. These tests further supported the concept to be used for developing an operational head restraint.

It was not until June 1977, after renewed interest in head/neck restraint development, that further testing of restraint configurations were resumed. For these tests the ring-shaped inflatable restraint bladder was investigated. Dynamic tests on the NAVAIRDEVCEN ejection tower, using human simulators (dummies) with single-bolt neck joints, showed that relatively high inflation pressures within the restraint bladder of over 15 psi (10.36 nt/cm^2) were required to prevent any head rotation whatsoever. (For these tests the maximum ejection acceleration was 14 G's and the weight of the dummy head was 12.75 lb [57.43 nt].) The question still remains as to whether or not the crewman's head should be restrained perfectly still or should it be allowed to rotate into the inflated bladder. Figures 3 and 4 show the comparisons of angular acceleration and angular velocity, respectively, for tests with and without the inflatable head/neck restraint. As expected, use of the restraint does substantially reduce the peak magnitude of both angular acceleration and angular velocity with the higher pressured bag offering the most restraint. It was estimated that a neck bladder inflated to 19 psi (13.1 nt/cm^2) would have been needed to prevent any head rotation of the dummy head.

The effectiveness of any device as a head restraint is based primarily on its capability of limiting angular rotation (thus limiting angular velocity and angular acceleration). It is theorized that the critical values of angular velocity and angular acceleration needed to produce concussion in man are 30 rad/sec and 1800 rad/sec^2, respectively[4]. Angular displacement may also play an important role in head/neck injury since there is evidence that neck injuries are caused by hypertension of neck muscles and hyperflexion of cervical

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3. *See page 3.*
4. *Mahone, R., P. Corrao, A. Ommaya, E. Hendler and M. Schulman; A Theory on the Mechanics of Whiplash-Produced Concussion in Primates. 40th Aerospace Medical Association Meeting, May 1969, pp 44-45.*

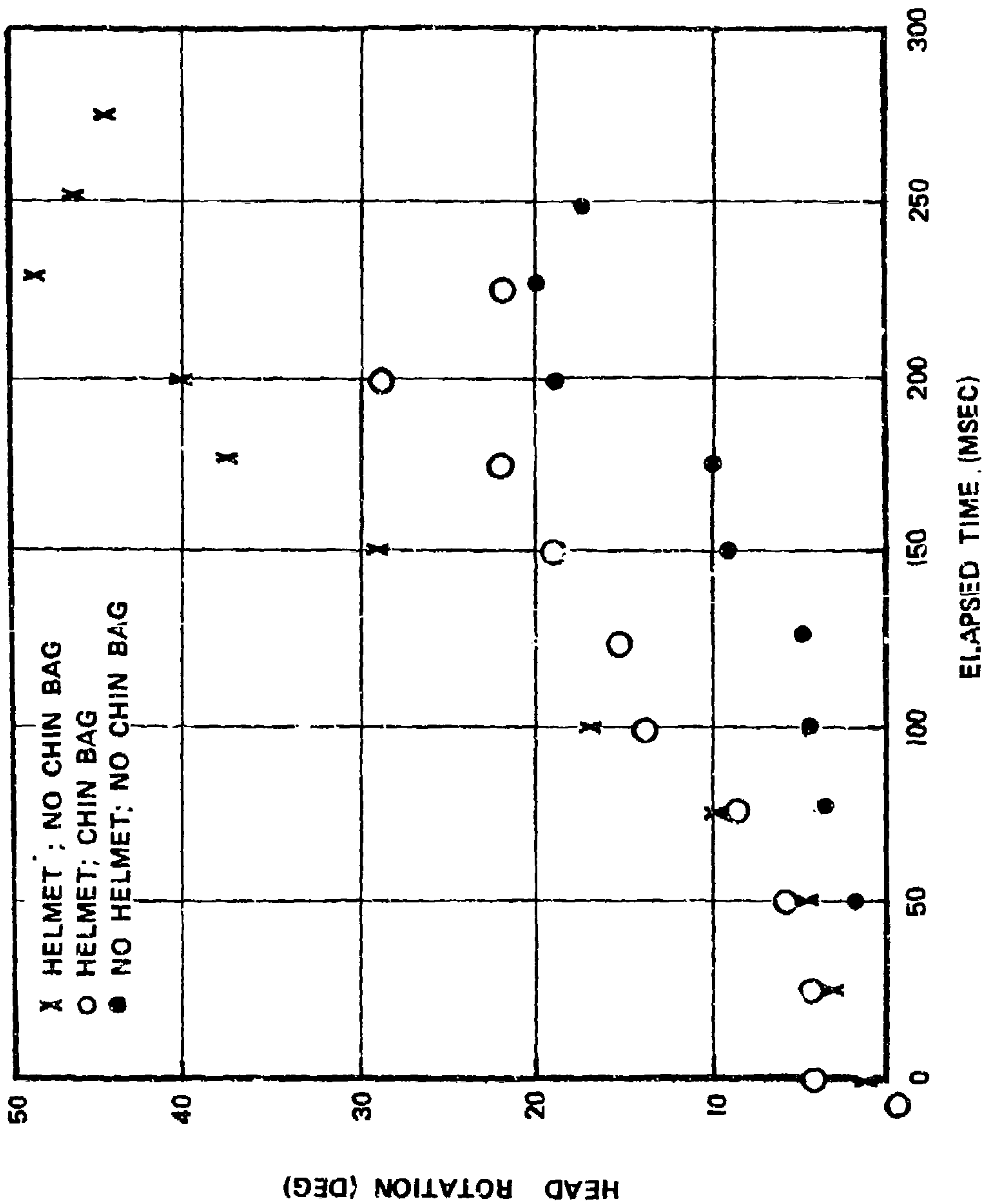

FIGURE 2 - Chin Bag Test Data

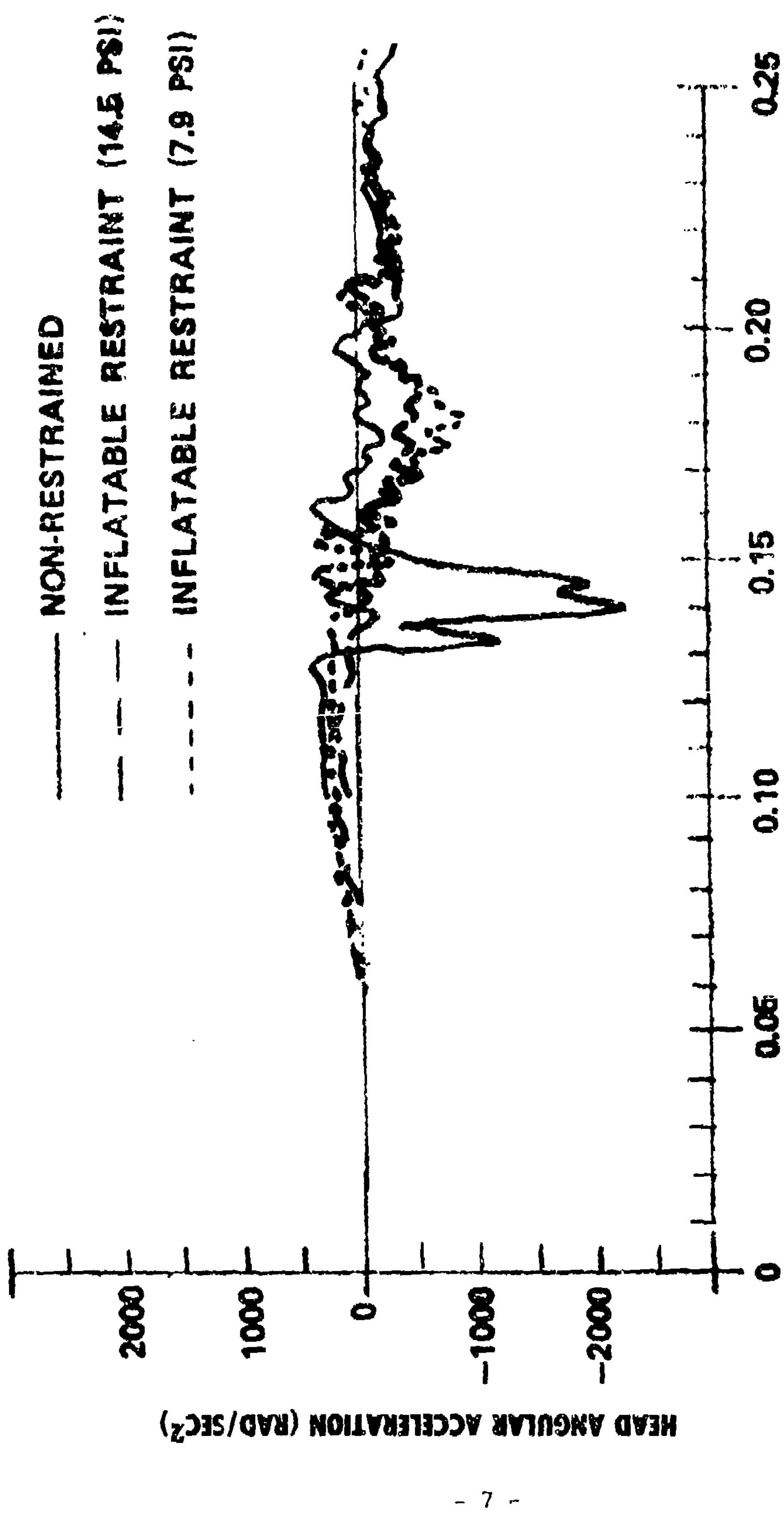

FIGURE 3 - Head Angular Acceleration Profiles

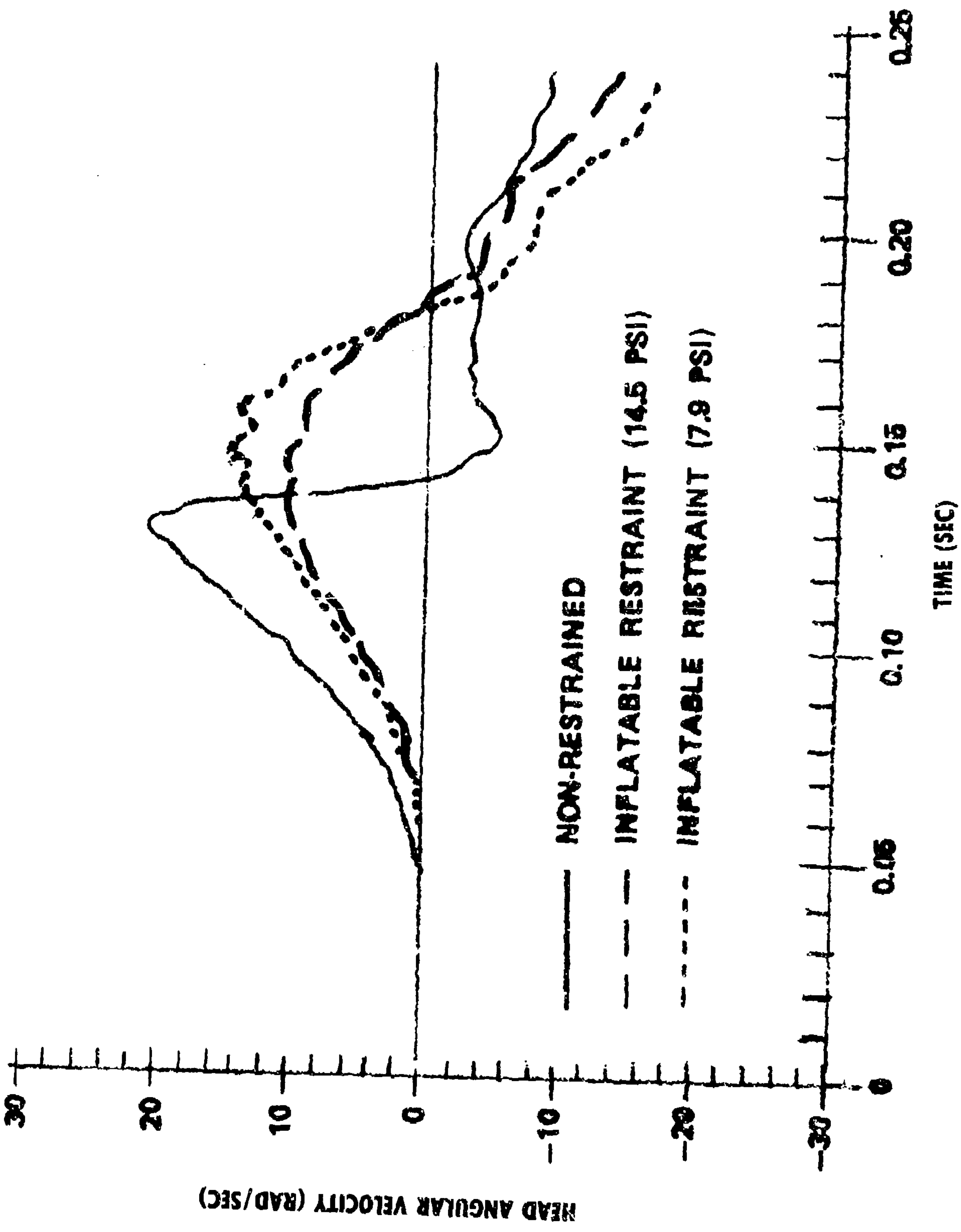

FIGURE 4 - Head Angular Velocity Profiles

vertebrae due to violent forward head rotation[5]. Figures 3 and 4 show that peak acceleration and velocity values are close to the theorized critical values (1800 rad/sec^2 and 30 rad/sec) for the nonrestrained dummy head.

The following text discusses the design philosophy pertaining to development and fabrication of the ACSTD inflation neck collar. (Throughout the remainder of this report, the terms: neck collar, neck bladder, neck bag, and head restraint will be used interchangeably.)

DESIGN CONSIDERATIONS

There are essentially five major design considerations pertaining to development of the inflatable head restraint:

1. Cost effectiveness.

2. Inflation technique.

3. Form and fit of the inflatable bladder to ensure head support.

4. Packaging of the deflated bladder.

5. Integration into life support equipment.

The last three design areas require the most attention in the development process since inflation technique is within current state-of-the-art technology, and cost effectiveness will depend primarily on complexity of the form, fit, fabrication and packaging of the neck bladder.

The remainder of this report discusses the design problems encountered in developing the neck collar along with the design approach which is expected to yield an effective system.

COST EFFECTIVENESS

Costs pertaining to the head restraint system must be kept low as compared to other life support systems. On a value vs cost basis, the head restraint would have a low rating when compared to a system such as a parachute recovery system or an ejection seat propulsion system. Both the recovery and propulsion systems have high values which justify a high cost for their development and operation since failure of either would lead to catastrophic results. However, a head restraint failure would be less likely to cause severe consequences since the crew member is still restrained by a conventional harness. Therefore, costs pertaining to development, production, and maintenance of the neck collar must be kept low if it is to be accepted into the fleet.

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5. *Ewing, C. L., King, A. I. and Prasad, P.; Structural Considerations of the Human Vertebral Column Under $+G_z$ Impact Acceleration, AIAA Paper No. 71-144 presented at AIAA 9th Aerospace Sciences Meeting, New York, Jan 1971.*

Maintenance and operational costs should be extremely low since components such as the bladder, package, gas lines, squib and gas generator have been designed to have shelf-lives measured in terms of years. In the aircraft cockpit, maintenance would essentially consist of visual inspection, and normal service life would be measured in years; no special test equipment will be needed during preventive and corrective maintenance procedures.

The bulk of the cost (beyond the development phase) would be fabrication and acquisition costs. Components of the inflator system such as gas lines, gas generator, squib, packaging fabric and bladder material are "off-the-shelf" items requiring very little or no development effort or redesign; therefore, the costs due to manufacturer's retooling and product development should be nominal.

The areas requiring concern for cost overrun are fabrication and packaging of the neck bladder. It is important that construction of the bladder and its packaging be kept simple. Patterns used in fabrication must not require intricate cutting procedures and long curing times for adhesive bonding.

INFLATION TECHNIQUE

An operational requirement of the neck collar is to have it inflate automatically at the time of ejection initiation. The neck bladder is to be packaged around the crewman's flight suit collar so that it will inflate around his neck and under his chin to support the head and prevent its rotation. The time from ejection initiation (when the lower ejection handle or face curtain is actuated) to initial upward movement of the ejection seat is usually 0.2 to 0.3 seconds (the delay time needed to jettison the canopy). Therefore, the restraint bladder must inflate during the delay. This inflation time can be easily attained since current inflator systems, such as those in automobile air bag systems, can inflate large volume bladders within 0.05 sec after receiving the initiation input signal.

Inflation tests using slightly modified "off-the-shelf" gas generators were conducted at NAVAIRDEVCEN in April and June of 1978. The gas generators were electrical squib-actuated solid propellant generators. The generators were to supply gas pressure in the range of 4.0 psi (2.76 nt/cm^2) to 8 psi (5.51 nt/cm^2) within 0.20 seconds. The results of the tests showed that the bladder received a peak pressure of 9.6 psi (6.62 nt/cm^2) within 0.06 seconds. The pressure decreased to 4.0 psi (2.76 nt/cm^2) at 0.55 seconds and finally stabilized at approximately 3.0 psi (2.07 nt/cm^2) in 1.55 seconds. There was no indication (from thermocouple measurements) of a temperature rise in the bladders during inflation; therefore, there is no thermal hazard to the crewman. Rate gyro measurements were recorded for angular velocity of the head (single-bolt neck joint on a dummy) caused by the force of the inflating bladder under the chin. The peak angular velocity recorded was 227°/sec (3.96 rad/sec) which is far less than the theorized 30 rad/sec maximum angular velocity which was referred to in the Introduction of this report.

The optimum inflation pressure has not been decided upon since there is still some question as to the degree of restraint desired. The degree of restraint is dependent on inflation pressure. It has been observed that low pressures, about 2 psi (1.38 nt/cm^2) to 4 psi (2.76 nt/cm^2) create a "spring back" or trampoline effect. Higher pressures, 6 psi (4.13 nt/cm^2) and upwards make the bladder very rigid. Ejection tower tests showed that although the angular velocity and angular acceleration, due to forward rotation of the head, was substantially reduced through use of the inflated neck bladder, the head still had the momentum to rebound into the head rest. It is expected that with the use of helmets and padded headrests, there will be no concern about rebound injury.

The inflation pressure may also vary slightly depending on ambient pressure. At high altitude ejections, where the atmospheric pressure is low (compared to sea level), the neck bladder may expand slightly and cause the internal pressure to decrease slightly. The bladder undergoes insignificant volume expansion after internal pressure surpasses approximately 6 psi (4.14 nt/cm^2).

Squib-actuated solid propellant gas generators are state-of-the-art technology and components are now being manufactured by several industrial organizations. The amount of solid propellant which creates the gas used for inflation depends on the volume in the bladder and the inflation pressure. The electrical squib initiates burning of the propellant within milliseconds after receiving an input from the ejection actuator. The gas used for inflation is non-toxic and does not reach a temperature high enough to injure the crewman.

The gas generator is located on the ejection seat and a flexible gas supply line is routed from generator to bladder. The supply line (approximately 3/8 inch [.925 cm] inside diameter) will be severed by a ballistically actuated guillotine or strap cutter at the time of seat-man separation during the ejection sequence. On some ejection seats, it may be possible to sever the supply line at the same time as the inertial reel straps are cut. A small check valve located near the bladder will prevent loss of gas from the bladder after the supply hose is severed. Figure 5 illustrates the design configuration of relevant components. The bladder will remain inflated to offer head restraint for parachute opening shock. During parachute descent, the crewman can pull the bladder off with a free hand if he feels that it inhibits his head motion.

For advanced engineering development, an attempt will be made to slow down the gas flow rate during inflation. Currently, peak pressure is reached within 0.06 secs; however, this sudden pressure increase was responsible for blowing off connection fittings along the gas supply line during two inflation tests. (Bladder did not inflate due to loss of gas pressure through supply line separation.)

An inflation time between 0.10 to 0.15 secs is now desired to alleviate the over-pressure in the supply line during the inflation process. It is expected that a slower burning propellant can be used to solve this problem.

INFLATABLE NECK BLADDER DESIGN

Design of an effective inflatable head restraint emphasizes the need for human engineering. Form and fit of the neck bladder to ensure head support is the most difficult task in development of the system.

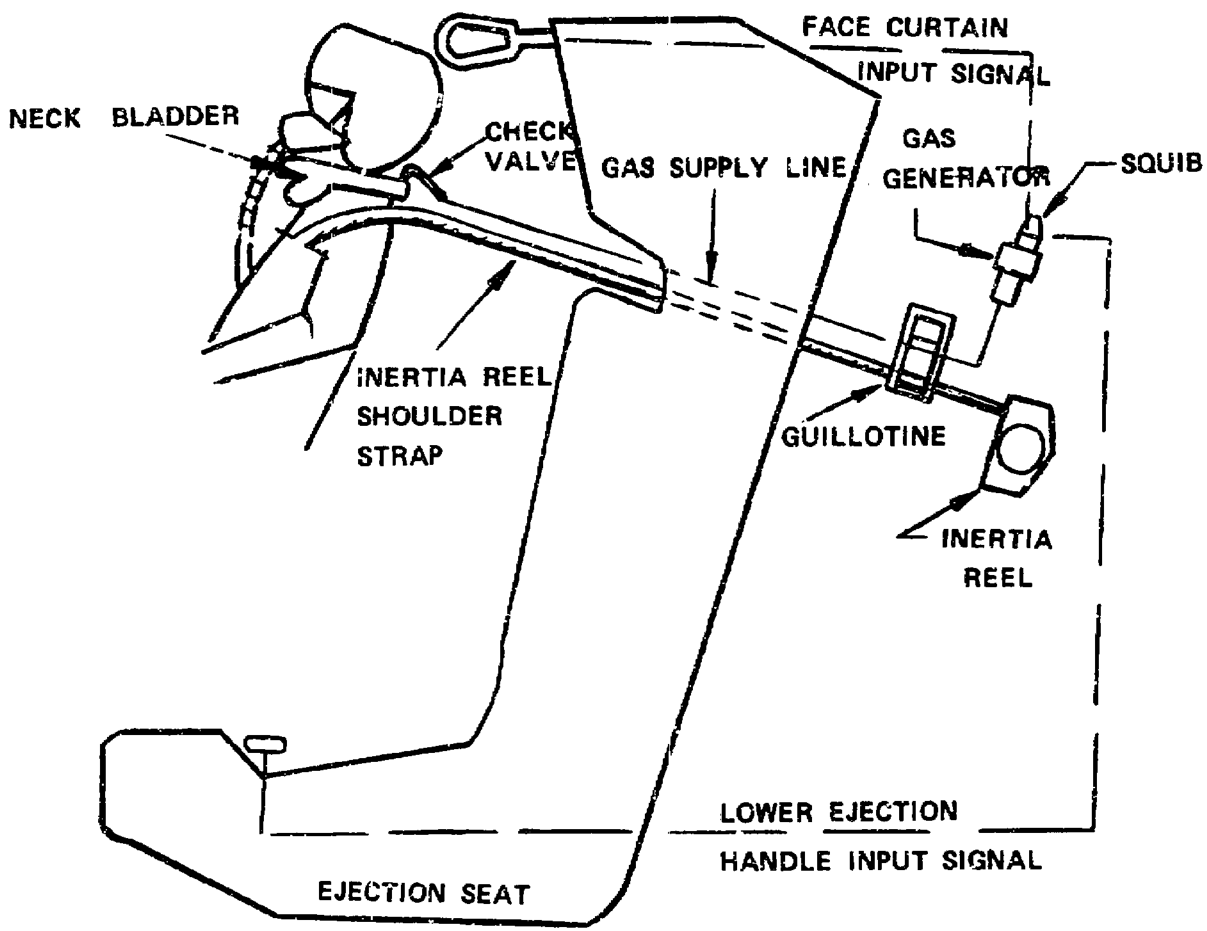

FIGURE 5 - Layout of Inflation System Components

To complicate matters, there is a large range of crewman anthropometric dimensions to which the inflatable bladder must be fitted. Dimensions of concern in fitting the inflated bladder are neck circumference, anterior neck length and mandible projection. These dimensions have to be considered for crewmen populations ranging from the 3rd percentile to 98th percentile populations. Table I lists the range of dimensions[6]. Like other wearing apparel, the neck collar will have to be fabricated in various sizes so that it fits all personnel; possibly, fabrication in four sizes will fit the entire range of crewmen. For development purposes, all neck collar models are being designed to the 50th percentile anthropometry.

The crux of the design approach in developing an inflatable head restraint is to support the crewman's chin with an inflated bladder or bag; along with chin support, the restraint should offer some support for lateral and backward rotation. Such a design requirement suggests a ring-shaped inflatable neck collar.

With the neck collar configuration, it is critical that the inner diameter of the ring-shaped bladder not be too large, otherwise the crewman's chin can slip inside the ring allowing his head to rotate forward. The advantage of the ring-shape design over a simple frontal chin bag design is that the ring does not slip away from the chin as easily as the chin bag. This is so because the ring is braced around the crewman's neck; whereas, the chin bag is only supported by a chin strap and can pivot along the strap causing the bag to slip or "squirt out" from under the mandible. An early ring-shaped neck collar is shown in figure 6. (This model is often called a "neck ring.") It was designed as three-layered rings and fabricated in an accordion-shaped configuration in an attempt to have the collar lay flat against the flight garment and to reduce packaging bulk. This design provided chin support and restricted head rotation, but due to excessive height of the bladder design the crewman helmet was pushed up and off his head. This condition can induce forward rotation of the helmet at the time of ejection thrust with the possibility that the front of the helmet can forcefully strike and possibly fracture the crewman's nose. Also, with the helmet pushed up and off the crewman's head, windblast or parachute opening forces could cause the helmet to completely separate from the crewman's head leaving him without head protection for the remainder of his parachute descent and rescue operations.

Refinement of the neck ring design required reducing the neck bladder height on the sides and back of the crewman's head. It was at these areas where the inflated bladder pushed against the helmet. The refined design has only one ring (2.0 inch, 3.08 cm cross-section diameter) encircling the crewman's neck. The portion of the ring under the crewman's chin was fabricated to two ring segments as shown in figures 7a and 7b. In designing the neck collar, it is necessary to support the chin by using the crewman's chest (sternum) as a supporting base for the bladder. A proper design allows the bladder to inflate under the chin and into his sternum. The refined neck collar design of figure 7 is more effective than the neck ring in figure 6 since it

6. *Hertzberg, H. T., Daniels, G. S., and Churchill, E.; Anthropometry of Flying Personnel-1950, WADC Tech Report 52-321, Wright-Patterson AFB, Ohio.*

TABLE I

ANTHROPOMETRIC MEASUREMENTS PERTAINING TO NECK COLLAR DESIGN

CREWMAN PERCENTILE	NECK CIRCUMFERENCE IN. (MM) 	ANTERIOR NECK LENGTH IN. (MM) 	JAW (MENTON) PROJECTION IN. (MM) 
3	13.8 (350.7)	2.1 (54.0)	1.4 (35.3)
25	14.7 (372.1)	3.0 (75.7)	1 7 (43.3)
50	15.1 (384.3)	3.4 (87.1)	1.9 (47.6)
75	15.6 (396.5)	3.8 (97.7)	2.0 (52.0)
98	16.7 (424.6)	4.9 (124.0)	2.4 (61.7)

FIGURE 6 - An Early Neck Collar Design - Three Layer Neck Ring

FIGURE 7a - Refined Neck Collar Design

FIGURE 7b - Refined Neck Collar Design

restrains the head but does not push against the helmet. The contour of the helmet fits within the contour of the inflated collar as depicted in figure 8.

The neck collar location does not interfere with life support equipment, specifically the oxygen mask and life preserver package. Figure 9 shows the location of the neck collar package with respect to the life preserver.

The neck ring and ring segments of the development model are constructed of simple flat patterns bonded together with adhesive cement. The bladder fabric is neoprene-coated nylon. The sealing process for the development phase uses the adhesive cement rather than heat sealing in order to obtain a stronger bond. Inflation pressures in bladders sealed with the adhesive cement can be as high as 25 psi (17.26 nt/cm^2), whereas heat sealed bladders have ruptured at 6 psi (4.13 $nt.cm^2$).

In the design of the inflatable neck collar, several design considerations materialize which are unique to the design of inflatables. Trial-and-error design and fabrication of models becomes necessary in achieving good form and fit. The desired form and fit of an inflated bladder is not easily assessed from the fabrication patterns because the fabric stretches and distorts upon inflation. For example, the inner diameter of the neck ring in its deflated mode decreases upon inflation, as shown in figure 10. The ends of the ring, although separated when deflated, will overlap upon inflation. Models fabricated of neoprene-coated nylon had an average reduction in the neck diameter upon inflation of about 12 percent ($D_2 \approx 0.88\ D_1$) for inflation pressures at 6 psi (4.1 nt/cm^2); for inflation pressures above 6 psi there was little deformation and stretch of the bladder. (No other fabrication material has been investigated, thus far, for comparison of distortion characteristics to the neoprene-coated nylon material.) The designer must also take care not to design any sharp edges into the bladder. Dimensional deformation can cause sharp corners on the patterns to push inwards against the neck as shown in figure 11. Of course, it is best to eliminate sharp corners not only for comfort purposes but because they are stress concentration areas during inflation and are difficult areas to properly seal and bond. Also, seams of the inflatable which rest against the neck must be smooth, as shown in figure 12.

Should a bladder be designed such that it becomes offset, as illustrated in figure 13, then the head is susceptible to snapping sideways; therefore, it is important to have a broad base under the chin and to prevent the restraint from shifting or sliding to the side of the jaw or around the neck. These problems are minimized in the neck ring design which offers stable support of the head.

PACKAGING TECHNIQUE

The neoprene-coated nylon fabrication material used for the neck restraint models has proven to be a strong and durable material; yet, it is light and pliable enough to be packaged around the crewmember's neck. The most difficult task to be overcome in fabricating the neck restraint bladder is to minimize excess bulk due to seams joined together with reinforcement tape and adhesive cement. An economical fabrication technique is needed, which not only will allow the bladder to inflate to a desired shape but also will provide a comfortable stowage package on the crewmember. Construction of the neck bladder

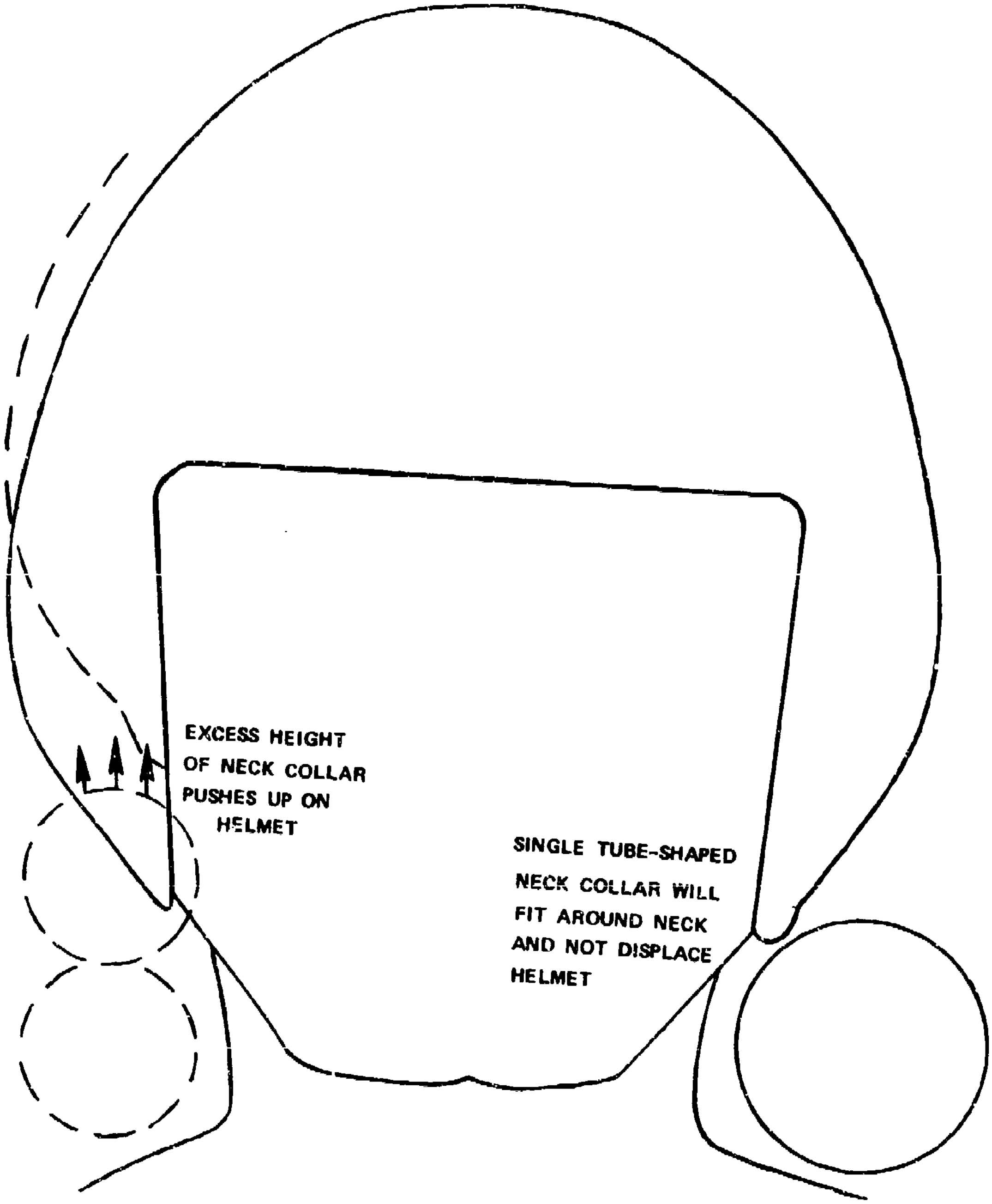

FIGURE 8 - Neck Ring Interference with Crewman's Helmet

FIGURE 9 - Location of Neck Collar With Respect to the Life Preserver Package

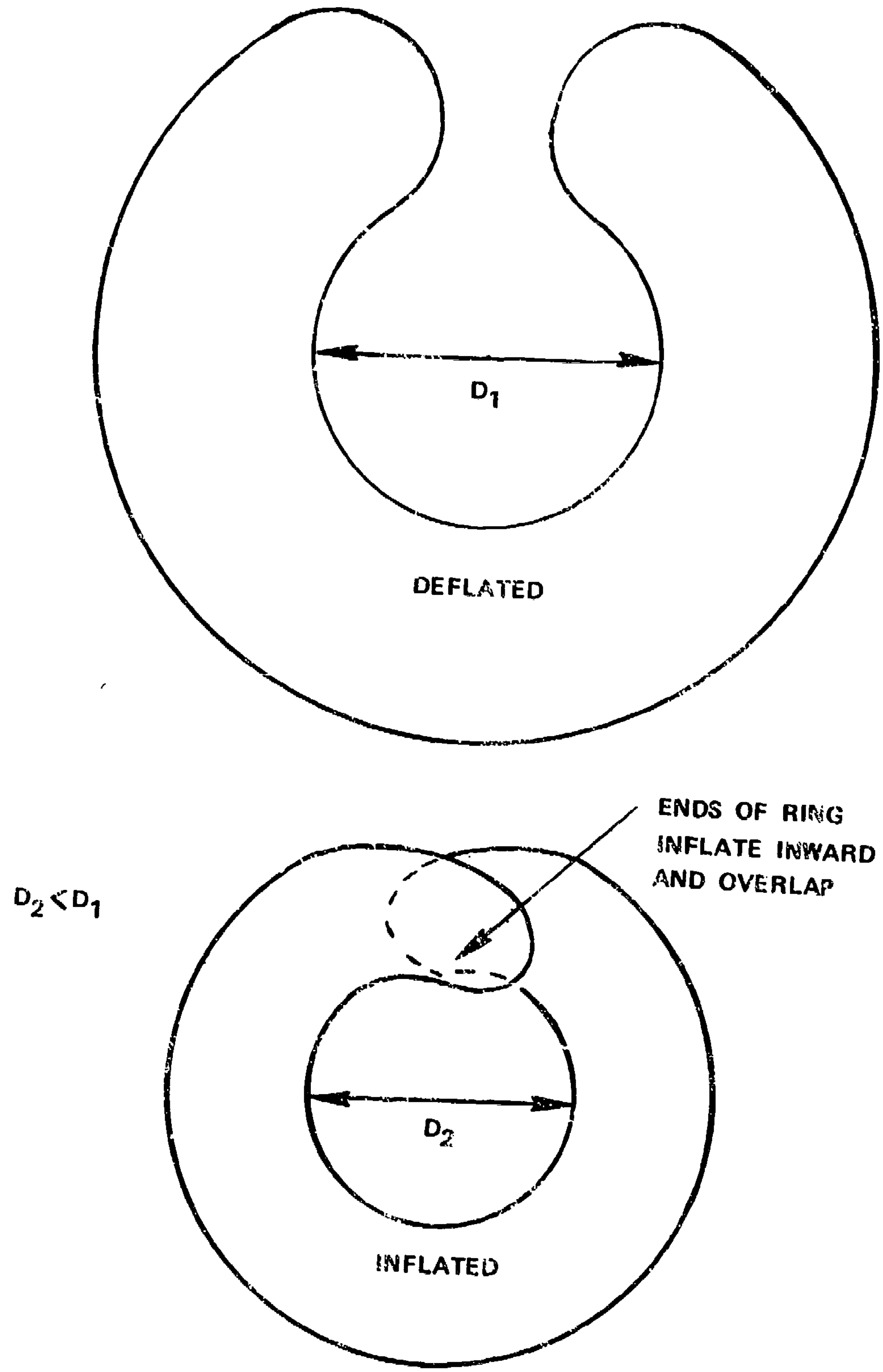

FIGURE 10 - Neck Ring Diameter Distortion From Deflated to Inflated Configuration

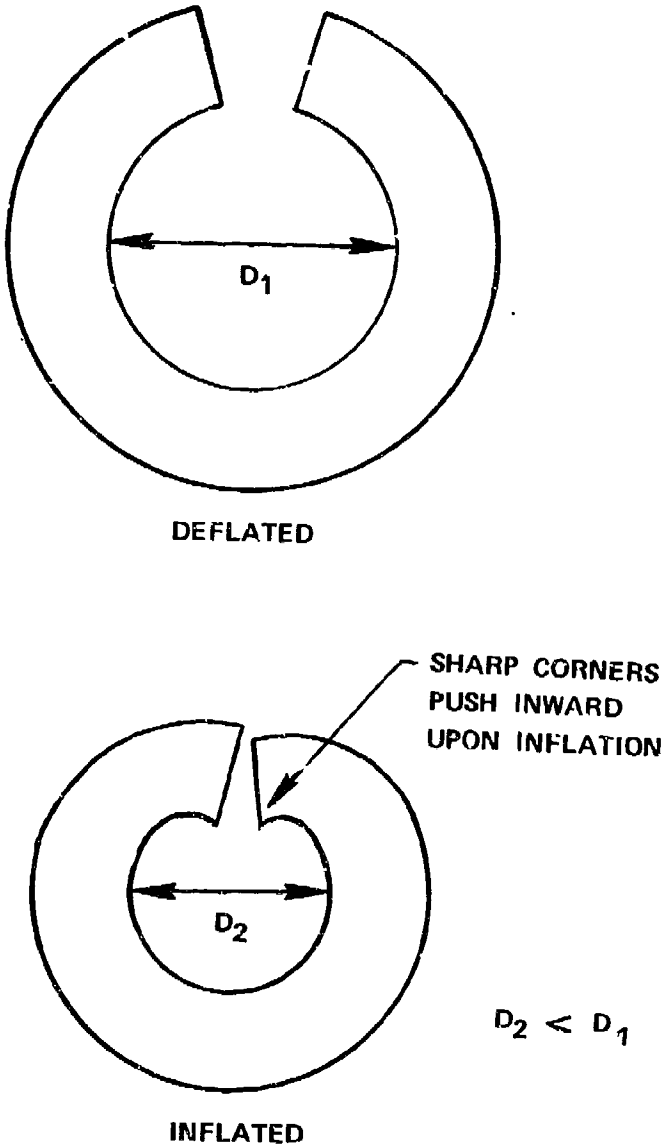

FIGURE 11 - Possibility of Neck Lacerations Due to Incorrectly Designed Neck Bladder

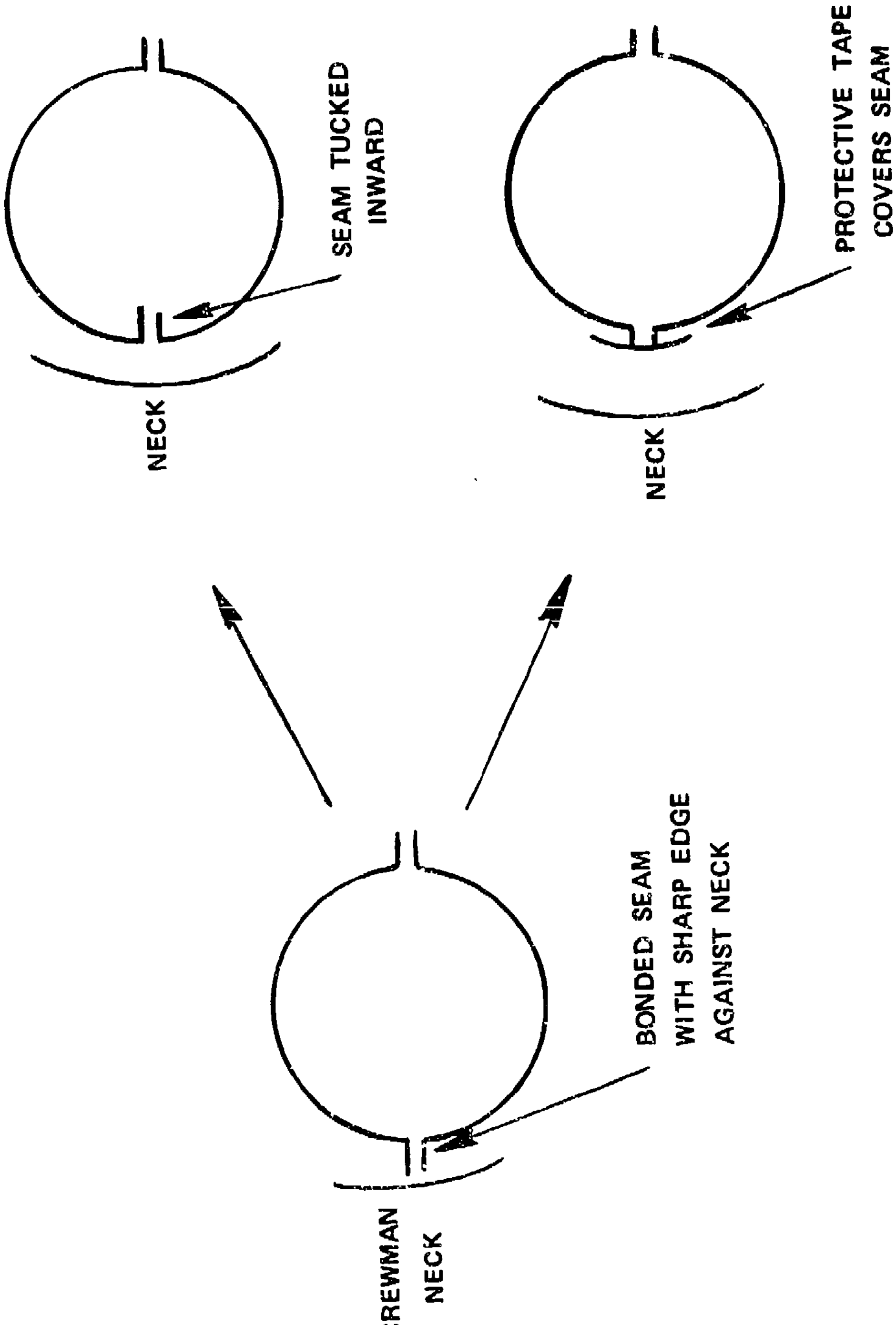

FIGURE 12 - Proper Seam Construction to Insure Comfort Upon Inflation

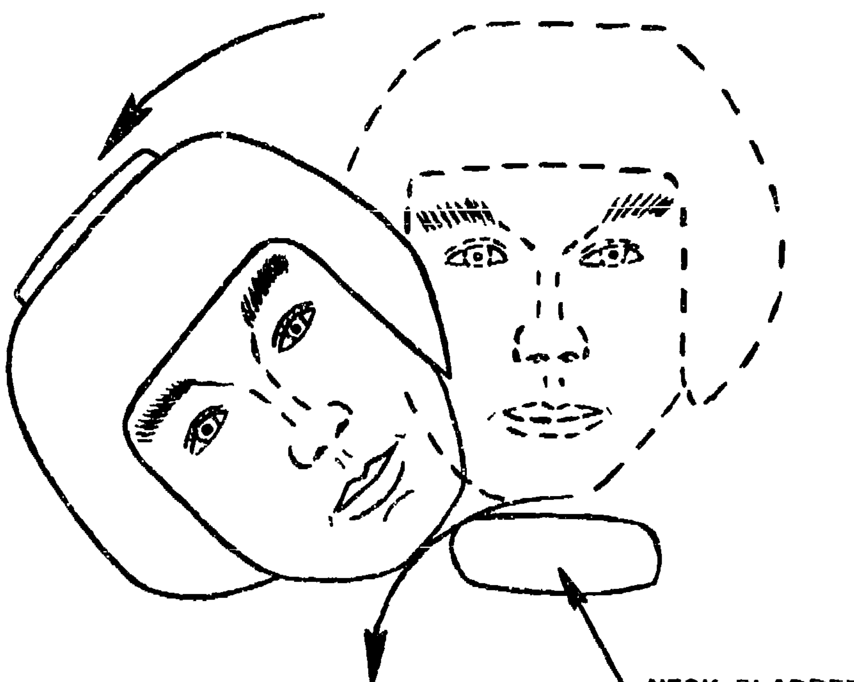

FIGURE 13 - Sideways Flexi(of the Head Due to Improper Positioning of the Neck Bladd r

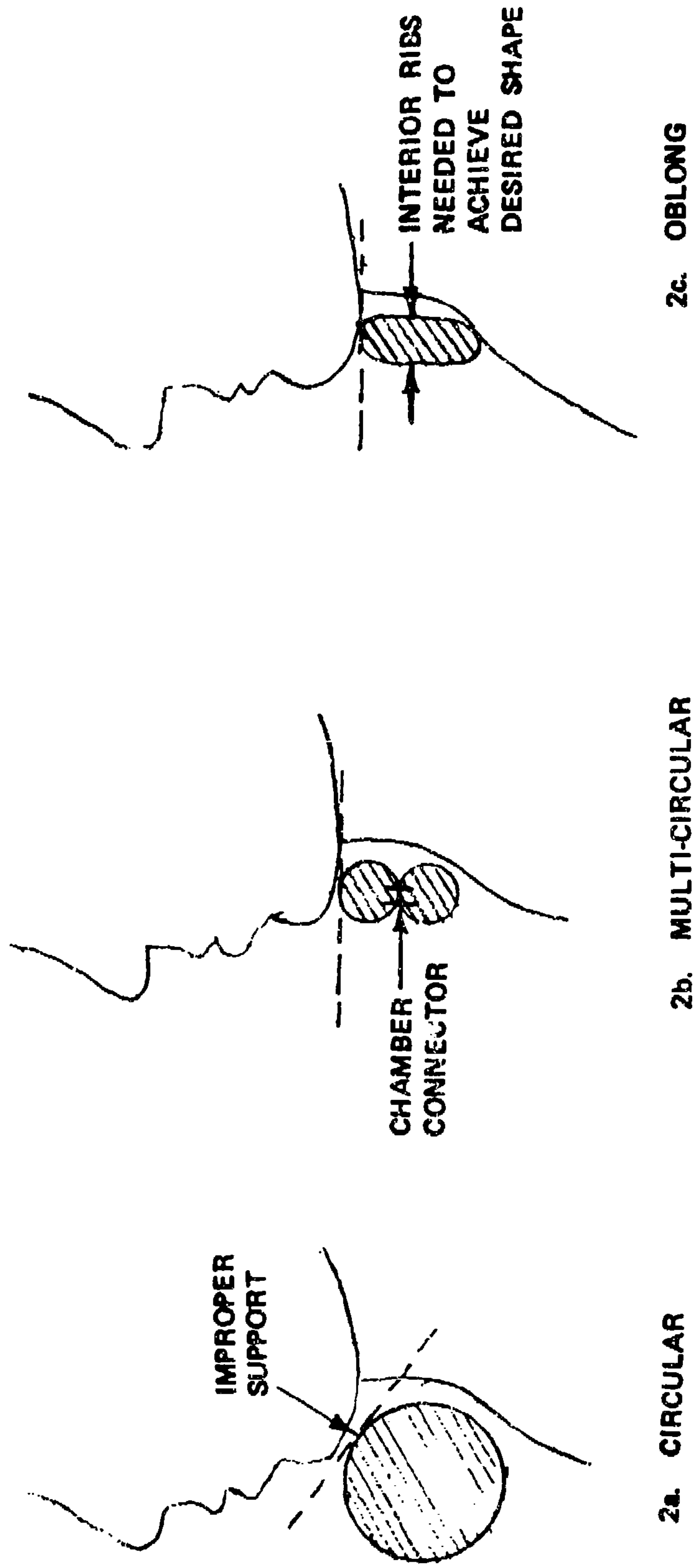

FIGURE 14 - Trade-off Design Between Performance and Fabrication

involves a trade-off between head support, packaging and fabrication. The simple circular cross-section shown in figure 14a offers the easiest fabrication process and a comfortable package, but cannot achieve proper head support since the crewman's chin will come to rest on the inside circumference of the bladder. This is due to the large circular construction necessary for using the sternum as a supporting base for the bladder. In figure 14b the double circular cross-section bladder shows better support because it fits further under the chin as well as bracing itself on the sternum; however, the fabrication of this configuration is more difficult than that of figure 14a and the packaging may be uncomfortable due to excessive bulk from gas chamber connections and adhesive bonded seams. The configuration of figure 14c offers good support, presents a compact and comfortable package, but is difficult to fabricate because of its oblong shape and circular fit around the crewman's neck. The neck bladder construction in figure 14c offers the best approach to the neck bladder design since it offers both head support and a comfortable stowage package; fabrication procedures pertaining to this construction are being investigated in an effort to develop a simple and inexpensive fabrication method.

Presently, the neck collar package (which is made of the same fabric as the flight suit) is to be an "add-on" to the collar of the suit. It can be fastened to the flight suit collar with Velcro or metal snaps. The collar extends across the flight suit zipper under the crewman's chin. All that is required of the crewman is to fasten down the front section on the side of the flight suit collar and plug in the flexible gas supply line to the inlet tube of the neck collar. The packaged inflatable when worn looks like a turtleneck collar. Upon inflation, the neck bladder pops through its package to support the crewman's head. The package seam is fastened together with Velcro and splits apart as the pressurized bladder forces its way out of the package. Inflation pressure of less than 1 psi (0.69 nt/cm^2) will split open the seam. Figures 15 through 18 show the neck collar package and its inflation sequence.

The neck collar is now being developed as a flight suit "add-on", but if necessary the flight suit collar can be easily altered for permanent storage of the neck bladder.

FUTURE EFFORTS

Currently, development of the inflatable head/neck restraint system has been halted due to the lack of research and development funds. When funds are appropriated, the next phase of development will consist of developing and fabricating a refined engineering prototype. Emphasis will be placed on achieving a comfortable neck collar package and developing a low-cost system.

A C K N O W L E D G M E N T

The author wishes to extend his appreciation to the following persons for their support in this development program: to Mr. B. Schrandt for fabrication of the inflatable neck ring models; to Mrs. C. Filipino for fabrication and alteration of the life support apparel and neck collar package; to Messrs W. Green, J. Murray and K. Scholl for development test assistance and test data acquisition.

FIGURE 15 - Crewman Donning the Neck Collar Package

FIGURE 16a - Fully Positioned Neck Collar Package

FIGURE 16b - Fully Positioned Neck Collar Package

FIGURE 17 - Neck Collar Beginning to Inflate

FIGURE 18 - Fully Inflated Neck Collar

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